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(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 527 966 B1

(12) EUROPEAN PATENT SPECIFICATION

(45) Date of publication of patent specification: 21.09.94 Bulletin 94/38

(51) Int. Cl.⁵: H04B 10/12, H04B 10/14

(21) Application number: 91920988.2

(22) Date of filing: 06.05.91

(86) International application number: PCT/IT91/00036

(87) International publication number: WO 91/18455 28.11.91 Gazette 91/27

(54) A MULTILEVEL COHERENT OPTICAL SYSTEM.

(30) Priority: 11.05.90 IT 4794990

(43) Date of publication of application: 24.02.93 Bulletin 93/08

(45) Publication of the grant of the patent: 21.09.94 Bulletin 94/38

(84) Designated Contracting States: AT BE CH DE DK ES FR GB GR IT LI LU NL SE

(56) References cited:
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(73) Proprietor: FONDAZIONE UGO BORDONI
Via Baldassarre Castiglione 59
I-00142 Roma (IT)

(72) Inventor: BETTI, Silvello
Via Castel Boverano, 73
I-00158 Roma (IT)
Inventor: CURTI, Franco
Via D. Vietri, 34
I-00149 Roma (IT)
Inventor: DE MARCHIS, Giancarlo
Via F. Fiorentini, 106
I-00159 Roma (IT)
Inventor: IANNONE, Eugenio
Via Innocenzo XI, 44
I-00165 Roma (IT)

(74) Representative: Flammenghi, Carlo et al
c/o Flammenghi-Flammenghi
Via Quattro Fontane, No. 31
I-00184 Roma (IT)

EP 0 527 966 B1

Description

The present invention relates to the communication systems using optical signals propagating through single-mode optical fibres and, in particular, a method of and an apparatus for generating, transmitting and receiving a multilevel optical signal.

Reliable and economically competitive, coherent optical transmission systems which can be made available at short and medium terms allow novel network architectures to be provided regarding long-distance and high-performance connections and multi-user LAN (Local Area Network) and MAN (Metropolitan Area Network) connections as well. In particular, the very large bandwidth of the single-mode optical fibres (thousands of GHz) can be suitably exploited by providing optical FDM-systems (Frequency Division Multiplexing) in which the selection of the desired channel can be obtained by shifting the frequency of the local oscillator. This allows passive optical networks with very high traffic capacity (thousands of gB/s) to be carried out. However, two important aspects restrict on one hand the bandwidth of the single channel and limit on the other hand the maximum number of channels which can be tuned by the user. In the first instance, in fact, the main restriction is due to the bandwidth of the photodiodes and the electronic circuits, while regarding the second instance it should be considered that the frequency range which can be tuned by the user depends on the tunability characteristics of the laser used as local oscillator.

In order to increase the information rate of any channel, systems have been provided in which the information to be transmitted is coded with more than two levels instead of being coded using only the two binary levels as it is customary for providing a high signal reception sensitivity. By transmitting multilevel signals an improvement of spectrum efficiency expressed in terms of information rate per unit of occupied band is obtained at the cost of a reduction of the sensitivity. The known systems with two or more levels resort to the digital amplitude and phase keying (APK) or to the digital phase shift keying (PSK) or polarization shift keying (SPSK) of the electrical component of the electromagnetic field associated to a coherent optical wave generated by a laser source.

In particular, according to the previous state of art, EP-A-0 277 427 discloses methods of and devices for processing an optical signal by altering the polarization state thereof under control of a signal at a predetermined scrambling frequency.

EP-A-0 280 075 discloses an optical low-noise superheterodyne receiver for modulated optical signals in which a received light signal is coupled to a coherent light signal having the same polarisation. Then such signals are combined so as to provide two pairs of optical signals, the signal of each pair having the same polarization perpendicular to that of the other pair, and fed to photoelements which provide electrical signals. Such electrical signals are then summed to each other after demodulation and after at least a phase shifting of one of such signals.

In "Electronics Letters" Vol. 26, No. 4 of 15th February 1990 there is disclosed the performance of coherent optical transmission systems using multilevel polarization modulation based upon equipower signal constellations at the vertices of regular polyhedra inscribed in to the Poincare's sphere.

The present invention seeks to provide a method of generating a multilevel signal with a better performance than the known systems with regard to the signal reception sensitivity on the same number of employed levels. Within such general aim the invention seeks to provide in particular a transmitting and a receiving apparatus carrying out the above mentioned method.

Such aims are achieved by the invention defined and characterized in general in the claims attached to the following description in which the present invention is disclosed by way of a non-limitative example with reference to the accompanying drawing, in which,

Fig. 1 is a block diagram of a transmitting apparatus for a multilevel optical signal according to the present invention;

Fig. 2 is a block diagram of the detecting stage and the intermediate frequency stage of a receiving apparatus according to the invention;

Fig. 3 is a block diagram of a multilevel signal processing stage based on the determination of the coefficients of the inverted Jones matrix in a receiving apparatus according to the invention;

Fig. 4 is a block diagram of a multilevel signal processing stage based upon an algorithm for providing and updating the values of the components of the reference vectors in the receiving apparatus of the invention;

Fig. 5 is a block diagram of the circuit of the stage of Fig. 4 for updating the values of the components of the reference vectors;

Fig. 6 is a diagram of the logarithm of the error probability P_e versus the number of the received photons per bit F for different values of the level number N;

Fig. 7 is a graph for the comparison of the sensitivity of the receiving apparatus (N-4Q) according to the invention, expressed in terms of the logarithm of the number of received photons per bit F versus the level

number N, with the sensitivity of a N-PSK apparatus (N-level Phase Shift Keying), a N-APK apparatus (N-level Amplitude and Phase Keying), and a N-SPSK apparatus (N-level Polarization Shift Keying with detection by Stokes parameters); and

Fig. 8 is a graph for the comparison of the sensitivity of the receiving apparatus according to the invention, expressed in terms of the logarithm of the number of received photons per bit F versus the level number N, with the limit performance of the transmitting apparatus defined by the Shannon expression of the transmitting channel capacity.

The electrical field $\underline{E}(t)$ of an electromagnetic wave having angular frequency ω_o and propagating through a single-mode optical fibre can be written as follows:

$$\underline{E}(t) = E_x(t)\underline{x} + E_y(t)\underline{y} = (x_1 + ix_2)\underline{x} + (x_3 + ix_4)\underline{y}\ e^{i\omega_o t}$$

where the phase terms x_1 and x_3 and the phase quadrature terms x_2 and x_4 are the components on the reference axes $\underline{x}$ and $\underline{y}$ of the polarization state, i.e. the vector representing the electrical field according to a given polarization. Vector X (x_1, x_2, x_3, x_4) can be associated to any state of such electromagnetic field, the components of which being such that:

$$x_1{}^2 + x_2{}^2 + x_3{}^2 + x_4{}^2 = P$$

where P is the transmitted optical power;

The schematic block diagram of a transmitter according to the invention is shown in Fig. 1: a laser source 1 generates a linearly polarized optical carrier having a frequency, for example, of 10^{14} Hz, so as to form an angle of 45° with respect to the reference axes $\underline{x}$ and $\underline{y}$. The phase of such optical field is modulated by a phase modulator 2 with a message, for example a voltage having a time variable amplitude $\alpha(t)$, which is generated by a coder 10 from a binary sequence m(t) representing an information to be transmitted. After the phase modulation the components of the polarization state on axes $\underline{x}$ and $\underline{y}$ are split by a polarization selection beam splitter 3. It should be noted that the reference axes $\underline{x}$ and $\underline{y}$ are defined by the orientation of splitter 3. In the upper branch the polarization of the signal is rotated by 90° by a polarization rotator 4 so as to align it with that of the signal in the lower branch. The phase of the latter signal is modulated by a modulator 5 with a message $\beta(t)$ also generated by coder 10. The two signals having the same polarization are mixed by a directional coupler 6, the outputs of which will be as follows:

$$s_1(t) = A/2\ e^{i[\omega_o t + \alpha(t)]}\,[e^{i\beta(t)} + e^{i\pi/2}]$$

$$s_2(t) = A/2\ e^{i[\omega_o t + \alpha(t)]}\,[e^{i\beta(t) + i\pi/2} + 1]$$

where A^2 is proportional to the transmitted optical power. The polarization state of signal s_1 is then rotated by 90° by a polarization rotator 7 so as to make it orthogonal to that of signal s_2, the phase of which is modulated by a modulator 8 with a message $\gamma(t)$ generated by coder 10. The resulting signals are then coupled by a polarization selection directional coupler 9 to provide the optical signal. to be transmitted through the fibre, the $\underline{x}$ and $\underline{y}$ polarization components of which have the following phase terms and phase quadrature terms:

$$x_1 = A\cos[\beta(t)/2 + \pi/4]\,\{\cos[\alpha(t) + \beta(t)/2 + \pi/4]\cos\gamma(t) + -\sin[\alpha(t) + \beta(t)/2 + \pi/4]\sin\gamma(t)\}$$

$$x_2 = A\cos[\beta(t)/2 + \pi/4]\,\{\cos[\alpha(t) + \beta(t)/2 + \pi/4\sin\gamma(t) + -\sin[\alpha(t) + \beta(t)/2 + \pi/4\cos\gamma(t)\}$$

$$x_3 = A\sin[\beta(t)/2 + \pi/4\cos[\alpha(t) + \beta(t)/2 + \pi/4]$$

$$x_4 = A\sin[\beta(t)/2 + \pi/4\sin[\alpha(t) + \beta(t)/2 + \pi/4]$$

where the function $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ can have values between 0 and 2π according to the selected codification method.

In particular, such functions are generated by coder 10 according to the following criteria. A succession of bits representing the information to be transmitted are fed into coder 10. Such succession is divided in groups of bits, each group of bits representing a symbol of the alphabet used by the coder. Thus the succession of bits is transformed in a succession of symbols. In case a N-level signal is transmitted and, for the sake of semplicity, under the assumption that N is a power of 2, each symbol is formed by m bits where m = 2 log N. Each symbol can be univocally associated to a point of the sphere in the four-dimensional space in which the electromagnetic field is represented, such point being determined by the vector $\underline{X}$ = = (x_1, x_2, x_3, x_4) or by a tern of generalized spherical coordinates α, β and γ and by the radius of the sphere, i.e. the square root of the transmitted optical power. Therefore, the transmission of a symbol corresponds to the transmission of a well defined state of the electrical field. As the succession of bits m(t) are fed into the coder, an association between symbols and points at the coordinates α, β and γ is effected; the latter are then entered into a digital-to -analog converter and transformed to the voltages $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ which are the control signals of the modulators 2, 5 and 8. It should be noted that the states of the electrical field are completely determined by the three angular coordinates as the transmitted optical power in the apparatus of Fig. 1 remains constant.

The block diagram of the stage detecting the optical signal and of the intermediate frequency stage of a receiving apparatus according to the invention is shown in Fig. 2.

The optical signal modulated in phase and polarization and generated by a transmitter of the type shown in Fig. 1 and transmitted through a single-mode fibre 11 is entered into a "90° optical hybrid" 13 along with a

coherent optical signal generated by a laser source operating as local oscillator 12. Such signal of the local oscillator having a frequency which differs from that of the transmitted signal carrier by a predetermined amount between 10^8 and 10^9 Hz is linearly polarized at 45° with respect to the reference axes $\underline{x}$ and $\underline{y}$. The 90° optical hybrid 13 is a known device having two inputs and two outputs and providing at one output the sum of the input signals and at the other output the sum of one input signal and the other input signal the phase of which is shifted by 90°. In such a case, therefore the output signals are the phase component and the phase quadrature component of the beat signal.

The $\underline{x}$ and $\underline{y}$ components of the polarization state of the output signals of the optical hybrid 13 are then split by polarization selection beam splitters 14 and 15 defining with their orientations the reference axes $\underline{x}$ and $\underline{y}$, and separately detected by four photodiodes 16, 17, 18 and 19. The four electrical intermediate frequency signals are then filtered by bandpass filters 20, 21, 22 and 23 centered about the intermediate frequency and having a double as high bandwidth as the figure rate R_s, i.e. the inverse of the transmission time of a symbol. A phase locked loop (PLL) 28 and four multipliers 24, 25, 26 and 27 allow the four intermediate frequency signals y_1, y_2, y_3 and y_4 at the outputs of the filters 20-23 to be translated to base band. Such signals are then fed to four lowpass filters 29, 30, 31 and 32 having the same bandwidth as the figure rate R_s so as to provide four base band signals z_1, z_2, z_3 and z_4 proportional to the estimated values of the components of vector $\underline{X}$ which are mainly impaired by the detection noise.

Two preferred embodiment of the processing apparatus have been proposed for providing and updating the estimated values of the components of vector $\underline{X}$ from the base band signals z_1, z_2, z_3 and z_4. Such apparatus allow the fluctuations of the polarization state of the optical signal due to the propagation through a single-mode fibre to be compensated by merely electronic techniques.

The operation of the first apparatus, the block diagram of which is shown in Fig. 3, is based on the determination of the inverse Jones matrix. As it is known, the effects due to the propagation through a single-mode optical fibre can be taken into account by the Jones unit operator providing the input-output relation between the polarization states of the optical field. Since such relation is linear, the application of the inverse Jones operator to the received signal allows the polarization state of the transmitted optical signal to be determined. Vector $\underline{Z}$ having the base band signals z_1, z_2, z_3 and z_4 as components is multiplied in block 33 by the inverse Jones matrix so as to provide the estimated values of the components of vector $\underline{X}$. The coefficients of the matrix are determined by an algorithm based upon the consideration that the fluctuations of the polarization state (0,1-1 Hz) due to the fibre birefringence are much slower than the figure rate (10-1000 Hz). The algorithm is implemented on the base of the calculation of the time averages of the signals z_1, z_2, z_3 and z_4 at blocks 34, 35, 36 and 37 in time intervals much longer than the symbol period, i.e. the transmission time of a symbol, and much shorter than the characteristic period of the polarization fluctuations. The elements of the Jones matrix depend linearly on the averages of the signals z_1, z_2, z_3 and z_4, as the coefficients of such linear relation are the averages of the four coordinates of the reference points evaluated in the set of the N feasible transmitted symbols and stored in block 38. Therefore, if the averages of the signals z_1, z_2, z_3, z_4 are known, a linear system of four equations with four unknown values can be implemented, the solution of which calculated in block 38 provides the real and imaginary parts of the coefficients of the Jones matrix, the inverse of which is then calculated in block 33. This algorithm causes the coefficients of the Jones matrix to be updated at the end of any time period at which the time averages of the signals z_1, z_2, z_3 and z_4 are evaluated, thus allowing the apparatus to follow the fluctuations of the polarization state due to the single-mode fibre birefringence.

The decision, i.e. the recognition of the state of the multilevel signal. received at a given time, is effected in block 39 by comparing the estimated vector ε of components ε_1, ε_2, ε_3 and ε_4 with the reference vectors corresponding to the feasible transmitted symbols, the components of which have been stored in block 39 when adjusting the apparatus. In particular, such comparison is effected by calculating the distances between the point on the surface of the sphere in the four-dimensional space corresponding to the estimated vector ε and the points determined by the reference vectors. Among the feasible transmitted symbols it is selected the symbol corresponding to the point determined by the reference vector having the shortest distance from the point of coordinates ε_1, ε_2, ε_3, and ε_4. The output signal of block 39 is fed to an user apparatus 50.

The operation of the second apparatus processing the multilevel signal is on the contrary based upon an algorithm allowing the values of the coordinates of the reference points to be initially determined and updated, i.e. the components of the reference vectors on the surface of the sphere in the four-dimensional Euclidean space. The schematic block diagram of such processing apparatus is shown in Fig. 4. The apparatus determines initially the reference vectors by means of a suitable initialization sequence and subsequently effects the continuous updating of the components of such vectors, the values of which are fed to block 45 in which a decision is taken by the above described procedure based upon the calculation of the distance between the point corresponding to the received symbol and the reference points. The decision circuit 45 in case of a N-level signal has 4N memory cells in which the components of the N reference vectors are stored. In the time

interval between two successive updatings the decision circuit 45 estimates the received symbol and associates it to any of the N symbols which can be transmitted. The updating of the components of any reference vector is carried out by calculating the mean value of the vector components which are estimated by the decision circuit during the updating interval as corresponding to that reference vector. At the end of any updating interval, which is chosen also in this case much shorter than the characteristic periods of the polarization fluctuations and much longer than the symbol period, the reference vectors are replaced by those corresponding to the novel components, the mean values of which calculated by the above described method have been stored in the 4N memory cells.

In the diagram of Fig. 4 the updating operation is effected by means of block 40 formed of four circuits 41, 42, 43 and 44, each of them comprises a switch 46 and N circuits 47 for the calculation of the mean value of the signal selected by the switch. After having estimated the received symbol, the decision circuit 45 supplies the control signal formed of the components of the reference vector corresponding thereto to the four blocks 41, 42, 43 and 44. Such control signal causes any base band signal z_1, z_2, z_3 and z_4 to be entered through switch 46 into circuit 47 for the calculation of the mean value corresponding to the reference symbol selected by the decision circuit 45 among the N feasible symbols which can be transmitted. Therefore, during the updating interval the outputs of the circuits 41, 42, 43 and 44 supply the signals which are to be used at the updating time to calculate the mean values of the components of the novel reference vectors which are then stored in the 4N memory cells of the decision circuit 45. The resulting processing signal of block 45 is supplied to an user apparatus 50.

The performance of the apparatus has been valued in view of the statistics of the detection noise. In order to optimize the performance, the reference states of the transmitted optical field have been selected such as to reduce to a minimum the optical. power necessary to achieve a predetermined error probability. In case of a N-level signal such choice consists in determining the position of N reference points on the sphere of the four-dimensional Euclidean space. From an analytical point of view the optimization of the performance can be achieved by an algorithm which minimizes the multi-variable function establishing the relationship between the error probability P_e and the coordinates of the N reference points. The problem cannot be analytically solved in closed form so that a numeric algorithm has been used to minimize the above mentioned multi-dimensional function for $3 \leq N \leq 32$.

Some results regarding feasible configurations of N reference points obtained by the minimization algorithm of multi-variable functions and using the downhill simplex method are shown in the following tables I, II, III, IV.

Table I

Level	$\phi°$	$\psi°$	$\theta°$
1	0.00	0.00	0.00
2	182.65	75.52	0.00
3	117.70	124.54	161.56
4	157.16	308.49	295.89
5	298.07	310.91	144.30

Table II

Level / Level	1	2	3	4	5
1	0.000	1.581	1.581	1.581	1.581
2	1.581	0.000	1.581	1.581	1.581
3	1.581	1.581	0.000	1.581	1.581
4	1.581	1.581	1.581	0.000	1.581
5	1.581	1.581	1.581	1.581	0.000

Table III

Level	φ°	ψ°	θ°
1	0.00	0.00	0.00
2	180.00	0.00	0.00
3	57.43	90.00	0.00
4	113.52	2.43	90.00
5	212.56	270.00	0.00
6	122.57	270.00	180.00
7	211.76	332.02	270.00
8	327.42	90.00	180.00

Table IV

Level \ Level	1	2	3	4	5	6	7	8
1	0.000	2.000	1.414	1.414	1.414	1.414	1.414	1.414
2	2.000	0.000	1.414	1.414	1.414	1.414	1.414	1.414
3	1.414	1.414	0.000	1.414	1.414	2.000	1.414	1.414
4	1.414	1.414	1.414	0.000	1.414	1.414	2.000	1.414
5	1.414	1.414	1.414	1.414	0.000	1.414	1.414	2.000
6	1.414	1.414	2.000	1.414	1.414	0.000	1.414	1.414
7	1.414	1.414	1.414	2.000	1.414	1.414	0.000	1.414
8	1.414	1.414	1.414	1.414	2.000	1.414	1.414	0.000

In particular Table I shows the of the angular coordinates ϕ, ψ and θ corresponding to the points of the sphere of the four-dimensional Euclidean space having standardized unit radius which are associated to the reference states of the electromagnetic field in case of an optimized five-level configuration. The angular co-

ordinates are bound to the components x_1, x_2, x_3 and x_4 defining the state of the electromagnetic field by the following relations:

$$x_1 = \cos\phi \cos\psi \cos\theta$$
$$x_2 = \cos\phi \cos\psi \sin\theta$$
$$x_3 = \cos\phi \sin\psi$$
$$x_4 = \sin\phi$$

Table II shows the values of the distances between the reference points on the sphere of standardized unit radius in case of a five-level configuration; in this case the distance of any couple of points is the same, and when that result is obtained, that is the best for symmetry reasons.

Table III shows the values of the angular coordinates ϕ. ψ and θ corresponding to the points on the sphere of the four-dimensional Euclidean space having standardized unit radius which are associated to the states of the electromagnetic field in case of an eight-level configuration.

Table IV shows the values of the distances between the reference points on the sphere having standardized unit radius in case of an eight-level configuration. In such case it was not possible to arrange the eight reference points on the four-dimensional sphere in such a way that they are at the same distance from one another. Nevertheless the optimum configuration has a high symmetry as any point has six first near points at a distance equal to the radius of the sphere multiplied by $\sqrt{2}$ and only one second near point at a double as high distance as the radius of the sphere.

In Fig. 6 the performance of the apparatus is shown by the logarithm of the error probability P_e versus the photon number per bit F for a number N of levels equal to 4,8 and 16, respectively.

In Fig. 7 the sensitivity of the apparatus is shown by the logarithm of the photon number per bit versus the number N of levels at an error probability of 10^{-9}. In such figure the performance of the apparatus according to the invention designated by N-4Q is compared with that of a N-level heterodyne PSK apparatus (N-PSK, N-Phase-Shift-Keying), a N-level heterodyne APK apparatus (N-APK, N-Amplitude-Phase-Keying), and a N-level polarization modulation apparatus with detection by Stokes parameters (N-SPSK, N-Stokes-Parameter-Shift-Keying), the former two being described in K. Feher "Digital MODEM Techniques", Advanced Digital Communications, Prentice-Hall Inc., Eaglewood Cliffs, New Jersey, 1987, the third one being described in an article of S. Betti, F. Curti, G. De Marchis, E. Iannone, "Multilevel Coherent Optical System Based On Stokes Parameters Modulation" which is being published on the Journal of Lightwave Technology.

In Fig. 8 the limit performance of the transmitting apparatus conditioned by the Shannon equation regarding the channel capacity is shown. The apparatus according to the invention suffers from a penalty with respect to the Shannon limit of 8.5 dB for N = 16, 7.4 dB for N = 32 and 7.8 dB for N = 64, respectively. The performance of the apparatus according to the invention with respect to the compared apparatus tends to improve as the number of levels increases as illustrated in the following Table V showing the improvement in dB of the performance of the apparatus according to the invention with respect to that of N-SPSK and N-PSK apparatus.

TABLE V

N	N-SPSK	N-PSK
8	1.4	3.8
16	2.3	5.4
32	3.0	9.3
64	3.8	10.9

Claims

1. A method of providing a multilevel signal on a coherent optical carrier in order to transmit information through a single-mode optical fibre by the modulation of the carrier, characterized in that the phase and the polarization of the carrier are modulated.

2. The method of claim 1, characterized by the following steps:
   - modulating the phase of the carrier with a first control signal;
   - dividing the carrier the phase of which is modulated in two orthogonal components representing the polarization state; and
   - modulating the phase of said orthogonal components by a second and a third control signals; said control signals being provided by coding a binary succession representing the information to be transmitted and formed of a plurality of symbols each of them representing a predetermined state of the multilevel signal to be transmitted.

3. The method of claim 2, characterized in that the predetermined states of the multilevel signal to be transmitted, each represented by the components of a four-dimensional vector defining a reference point on the surface of the sphere of the four-dimensional Euclidean space having a radius equal to the square root of the transmitted optical mean power, are determined by selecting the respective reference points such as to minimize the multi-variable function correlating the bit error probability with the coordinates of said reference points.

4. An optical transmitter for the transmission of multilevel signals formed according to the method of claim 1, comprising a coherent light source (1) adapted to generate the optical carrier and a modulation signal generator (10), characterized in that it further comprises a first phase modulator (2) adapted to modulate the phase of said carrier, and a polarization modulator (3-8) coupled to the output of the first phase modulator (2), and the modulation signal generator (10) has an output connected to the first phase modulator (2) and at least one output connected to the polarization modulator (3-8) to provide thereto phase and polarization modulation control signals.

5. The optical transmitter of claim 4 for carrying out the method according to claim 2 or 3, characterized in that between the first phase modulator (2) and the polarization modulator (3-8) a polarization selection beam splitter (3) is connected which is adapted to split the two orthogonal components of the polarization state of the carrier, and that the polarization modulator (3-8) comprises a polarization rotator (4) rotating by 90° the polarization of one of such components, a second phase modulator (5) adapted to modulate the phase of the other component, a 2x2 directional coupler (6) supplying to the output ports the superimposed input signals, a second polarization rotator (7) rotating by 90° the polarization of one of the two input signals of the directional coupler (6), and that the modulation signal generator (10) comprises a coder (10) supplying from the binary sequence the control signals to the three phase modulators (2, 5, 8), and that the output of the polarization modulator (3-8) is connected to a polarization selection directional coupler (9) for combining again the orthogonal components of the polarization state and for entering the obtained signal into the optical single-mode fibre (11) acting as transmission channel.

6. An optical receiver for receiving multilevel signals formed according to the method of claim 1 and including a first stage consisting of an optical local oscillator (12), a 90° optical hybrid (13), two separators (14, 15) of the orthogonal polarization components, and four photodiodes (16-19) for the detection of said signals, said first stage being coupled to the optical fibre (11) and being adapted to carry out the heterodyne detection of the phase terms and the phase quadrature terms of the beat signal generated from the polarized signal received by the optical fibre (11) and the optical local oscillator signal, characterized in that said first stage further comprises four bandpass filters (20-23) centered about the intermediated frequency of the signals detected by said photodiodes (16-19), and a second stage (24-32) is provided coupled to said first stage and adapted to demodulate the received signals for providing the multilevel signal, including an electronic device converting the intermediate frequency signals of said bandpass filters (20-23) to base band and comprising a phase locked loop (28), four multipliers (24-27) and four bandpass filters (29-32), and a processing circuit is coupled to said second stage and adapted to compare said multilevel signal with predetermined reference signals.

7. The optical receiver of claim 6 for receiving multilevel signals formed according to the method of claim 2 or 3, characterized in that said processing circuit based upon the evaluation of the inverse Jones matrix comprises four circuits (34-37) receiving at their inputs the base band signals from the bandpass filters (29-32), calculating the time averages of said signals in time periods much longer than the symbol period and much shorter than the characteristic periods of the polarization fluctuations, and supplying at their outputs four signals representing said time averages, a circuit for the inversion of the Jones matrix (33) receiving at its input the above mentioned base band signals and supplying at its output the estimated

values of the transmitted multilevel signal, a calculation circuit (38) receiving at its input the four signals representing the time averages of the base band signals and comparing said signals with the feasible transmitted symbols forming the predetermined reference signals stored in the circuit itself so as to calculate the coefficients of the Jones matrix and to supply them to the circuit for entering the Jones matrix (33), and a decision circuit (39) receiving at its input the estimated values of the transmitted multilevel signal and comparing said values with the feasible transmitted symbols stored in the circuit itself so as to assign to each estimated value one of the feasible transmitted symbols.

8. The optical receiver of claim 6 for receiving multilevel signals formed according to the method of claim 2 or 3, characterized in that said processing circuit comprises first circuit means (45) for determining initially the reference signals by an initialization sequence, second circuit means (40) adapted to calculate the time average of the base band signals in time periods much longer than the symbol period and much shorter than the characteristic period of the polarization state fluctuations, and to store and to update the components of the reference signals, the decision circuit means (45) being adapted to compare the time averages of the base band signals with the reference signals and to assign to each of them one of the feasible transmitted symbols, the updating time period being much shorter than the characteristic period of the polarization fluctuations and much longer than the symbol period.

Patentansprüche

1. Verfahren zum Erzeugen eines mehrstufigen Signals auf einem kohärenten optischen Träger zur Informationsübertragung durch eine Monomode-Lichtleitfaser durch die Modulation des Trägers, dadurch gekennzeichnet, daß die Phase und die Polarisation des Trägers moduliert werden.

2. Verfahren nach Anspruch 1, gekennzeichnet durch die folgenden Schritte:
   - Modulieren der Phase des Trägers mit einem ersten Steuersignal;
   - Teilen des Trägers, dessen Phase moduliert wird, in zwei orthogonale, den Polarisationszustand wiedergebende Komponenten; und
   - Modulieren der Phase der orthogonalen Komponenten durch ein zweites und ein drittes Steuersignal;

   wobei die Steuersignale erzeugt werden, indem eine der zu übertragenden Information entsprechende und aus einer Anzahl von Symbolen gebildete binäre Sequenz kodiert wird, und wobei jedes der Symbole einem verbestimmten Zustand des zu übertragenden nehrstufigen Signals entspricht.

3. Verfahren nach Anspruch 2, dadurch gekennzeichnet, daß die vorbestimmten Zustände des zu übertragenden mehrstufigen Signals, die jeweils durch die Komponenten eines vierdimensionalen Vektors dergestellt werden, der einen Bezugspunkt auf der Oberfläche der Kugel des vierdimensionalen Euklidischen Raums bildet, die einen Radius gleich der Quadratwurzel der übertragenen mittleren optischen Leistung aufweist, durch Auswählen der jeweiligen Bezugspunkte derart bestimmt werden, daß die Mehrvariablen-Funktion, welche die Bitfehlerwahrscheinlichkeit mit den Koordinaten der Bezugspunkte in Beziehung setzt, möglichst klein wird.

4. Optischer Sender zum Übertragen von mehrstufigen Signalen, die nach dem Verfahren gemäß Anspruch 1 gebildet sind, mit einer kohärenten Lichtquelle (1) zum Erzeugen des optischen Trägers und einem Modulationssignalgenerator (10), dadurch gekennzeichnet, daß er ferner aufweist einen ersten Phasenmodulator (2) zum Modulieren der Phase des Trägers, sowie einen Polarisationsmodulator (3-8), der mit dem Ausgang des ersten Phasenmodulators (2) gekoppelt ist, und daß der Modulationssignal-Generator (10) mit einem Ausgang an den ersten Phasenmodulator (2) und wenigstens einem Ausgang an dem Polarisationsmodulator (3-8) angeschlossen ist, um auf diesen Phasen- und Polarisationsmodulationssteuerstignale zu geben.

5. Optischer Sender nach Anspruch 4 zur Durchführung des Verfahrens nach Anspruch 2 oder 3, dadurch gekennzeichnet, daß zwischen dem ersten Phasenmodulator (2) und dem Polarisationsmodulator (3-8) ein Polarisationsauswahl-Strahlungsteiler (3) angeschlossen ist, der zum Teilen der zwei orthogonalen Komponenten des Polarisationszustandes des Trägers geeignet ist, und daß der Polarisationsmodulator (3-8) einen Polarisationsrotator (4), der die Polarisation einer dieser Komponenten um 90° dreht, einen zweiten Phasenmodulator (5) zum Modulieren der Phase der anderen Komponente, einen 2x2-Richtungskoppler (6), der auf die Ausgangsöffnungen die überlagerten Eingangssignale gibt, und einen zweiten Po-

larisationsrotator (7) aufweist, der die Polarisation eines der beiden Eingangssignale des Richtungskopplers (6) um 90° dreht, und daß der Modulationssignalgenerator (10) einen Kodierer (10) aufweist, der von der binären Sequenz die Steuersignale auf die drei Phasenmodulatoren (2, 5, 8) gibt, und daß der Ausgang des Polarisationsmodulators (3-8) mit einem Polarisationswahl-Richtungskoppler (9) verbunden ist, um die orthogonalen Komponenten des Polarisationszustands wieder zu kombinieren und das erhaltene Signal in die Monomode-Lichtleitfaser (11) zu geben, die als Übertragungskanal wirkt.

6. Optischer Empfänger zum Empfangen von mehrstufigen Signalen, die nach dem Verfahren gemäß Anspruch 1 gebildet sind, mit einer ersten Stufe, die aus einem optischen Empfanqsoszillator (12), einer optischen 90°-Gabelschaltung (13), zwei Separatoren (14, 15) der orthogonalen Polarisationskomponenten und vier Photodioden (16-19) zum Erfassen der Signale besteht, wobei die erste Stufe mit der Lichtleitfaser (11) gekoppelt und geeignet ist, die Überlagerungserfassung der Phasenterme und der Phasenquadraturterme des Überlagerungssignals durchzuführen, das aus dem von der Lichtleitfaser (11) empfangenen polarisierten signal und dem optischen Empfangsoszillator-Signal erzeugt wird, dadurch gekennzeichnet, daß die erste Stufe Vier Bandpaßfilter (20-23) aufweist, die um die gemittelte Frequenz der von den Photodioden (16-19) erfaßten Signale zentriert sind, und daß eine zweite Stufe (24-32) vorgesehen ist, die mit der ersten Stufe gekoppelt und geeignet ist, die empfangenen Signale zur Erzeugung des mehrstufigen Signals zu demodulieren, einschließlich einer elektronischen Anordnung, welche die Signale mit gemittelter Frequenz der Bandpaßfilter (20-23) auf das Basisband umsetzt und einen Phasenregelkreis PLL (28), vier Multiplier plier (24-27) und vier Bandpaßfilter (29-32) aufweist, und daß eine Verarbeitungsschaltung mit der zweiten Stufe gekoppelt und geeignet ist, das mehrstufige Signal mit vorbestimmten Bezugssignalen zu vergleichen.

7. Optischer Empfänger nach Anspruch 6 zum Empfangen von mehrstufigen Signalen, die nach dem Verfahren gemäß Anspruch 2 oder 3 gebildet sind, dadurch gekennzeichnet, daß die Verarbeitungsschaltung auf der Basis der Auswertung der inversen Jones-Matrix aufweist vier Schaltungen (34-37), die an ihren Eingängen die Basisband-Signale aus den Bandpaßfiltern (29-32) empfangen, die Zeitmittel der Signale in Zeitperioden berechnen, die viel länger sind als die Symbolperiode und viel kürzer als die charakteristischen Perioden der Polarisationsschwankungen, und an ihren Ausgängen vier den Zeitmitteln entsprechende Signale abgeben, eine Schaltung zur Inversion der Jones-Matrix (33), die an ihrem Eingang die oben erwähnten Basisband-Signale empfängt und an ihrem Ausgang die geschätzten Werte des übertragenen mehrstufigen Signals liefert, eine Berechnungsschaltung (38), die an ihrem Eingang die vier den Zeitmitteln der Basisband-Signale entsprechenden Signale empfängt und diese Signale mit den brauchbaren übertragenen Symbolen vergleicht, welche die in der Schaltung selbst gespeicherten vorbestimmten Bezugssignale bilden, um die Koeffizienten der Jones-Matrix zu berechnen und sie auf die Schaltung zur Eingabe der Jones-Matrix (33) zu geben, sowie eine Entscheidungsschaltung (39), welche an ihrem Eingang die geschätzten Werte des übertragenen mehrstufigen Signals empfängt und diese Werte mit den brauchbaren übertragenen Symbolen vergleicht, die in der Schaltung selbst gespeichert sind, um jedem geschätzten Wert eines der brauchbaren übertragenen Symbole zuzuordnen.

8. Optischer Empfänger nach Anspruch 6 zum Empfangen mehrstufiger Signale, die nach dem Verfahren gemäß Anspruch 2 oder 3 gebildet sind, dadurch gekennzeichnet, daß die Verarbeitungsschaltung aufweist eine erste Schaltanordnung (45) zur anfänglichen Bestimmung der Bezugssignale durch eine Auslösesequenz, eine 2weite Schaltanordnung (40) zur Berechnung des Zeitmittels der Basisband-Signale in Zeitperioden, die viel länger sind als die Synbolperiode und viel kürzer als die charakteristische Periode der Polarisationszustandsschwankungen, sowie zum Speichern und Aufdatieren der Komponenten des Bezugssignals, wobei die Entscheidungsschaltanordnung (45) geeignet ist, die Zeitmittel der Basisband-Signale mit den Bezugssignalen zu vergleichen und jedem derselben eines der brauchbaren übertragenen Symbole zuzuordnen, und wobei die Aufdatier-Zeitperiode viel kürzer ist als die charakteristische Periode der Polarisationsschwankungen und viel länger als die Symbolperiode.

Revendications

1. Procédé de formation d'un signal multiniveau sur un signal optique porteur cohérent pour transmettre de l'information par l'intermédiaire d'une fibre optique à mode unique par la modulation du signal porteur, caractérisé en ce que la phase et la polarisation du signal porteur sont modulées.

2. Procédé selon la revendication 1, caractérisé par les étapes suivantes :
   - modulation de la phase du signal porteur par un premier signal de commande ;
   - division du signal porteur, dont la phase est modulée, en deux composantes orthogonales représentant l'état de polarisation ; et
   - modulation de la phase des dites composantes orthogonales par des second et troisième signaux de commande ;

   les dits signaux de commande étant obtenus en codant une succession binaire représentant l'information à transmettre et formée de plusieurs symboles, dont chacun représente un état prédéterminé du signal multiniveau à transmettre.

3. Procédé selon la revendication 2, caractérisé en ce que les états prédéterminés du signal multiniveau à transmettre, représentés chacun par les composantes d'un vecteur à quatre dimensions déterminant un point de référence sur la surface de la sphère de l'espace euclidien à quatre dimensions dont le rayon est égal à la racine carrée de la puissance optique moyenne transmise, sont déterminés en sélectionnant les points de référence respectifs de façon à minimiser la fonction multi-variables qui fait correspondre la probabilité d'erreur de bit avec les coordonnées des dits points de référence.

4. Transmetteur optique pour la transmission de signaux multiniveau formés selon le procédé de la revendication 1, comprenant une source de lumière cohérente (1) conçue pour produire le signal optique porteur et un générateur de signaux de modulation (10), caractérisé en ce qu'il comprend de plus un premier modulateur de phase (2) conçu pour moduler la phase du dit signal porteur, et un modulateur de polarisation (3-8) couplé à la sortie du premier modulateur de phase (2), et en ce que le générateur de signaux de modulation (10) présente une sortie reliée au premier modulateur de phase (2) et au moins une sortie reliée au modulateur de polarisation (3-8) pour lui fournir des signaux de commande de modulation de la phase et de la polarisation.

5. Transmetteur optique selon la revendication 4 pour la mise en oeuvre du procédé selon la revendication 2 ou 3 caractérisé en ce que, entre le premier modulateur de phase (2) et le modulateur de polarisation (3-8), est relié un diviseur de rayons (3) pour sélection de polarisation qui est conçu pour diviser les deux composantes orthogonales de l'état de polarisation du signal porteur, et en ce que le modulateur de polarisation (3-8) comprend un appareil rotateur de polarisation (4) qui fait tourner de 90° la polarisation de l'une de ces composantes, un second modulateur de phase (5) conçu pour moduler la phase de l'autre composante, un coupleur directionnel 2x2 (6) qui fournit aux orifices de sortie les signaux d'entrée superposés, un second appareil rotateur de polarisation (7) qui fait tourner de 90° la polarisation de l'un des deux signaux d'entrée du coupleur directionnel (6), en ce que le générateur de signaux de modulation (10) comprend un codeur (10) qui fournit, à partir de la séquence binaire, les signaux de commande aux trois modulateurs de phase (2,5,8), et en ce que la sortie du modulateur de polarisation (3-8) est reliée à un coupleur directionnel (9) de sélection de polarisation pour combiner encore les composantes orthogonales de l'état de polarisation et pour faire entrer le signal obtenu à l'intérieur de la fibre optique à mode unique (11) qui agit à la façon d'un canal de transmission.

6. Récepteur optique pour la réception de signaux multiniveau formés selon le procédé de la revendication 1 et comprenant un premier étage qui consiste en un oscillateur optique local (12), un hybride optique à 90° (13), deux séparateurs (14,15) des composantes orthogonales de polarisation, et quatre photodiodes (16,19) pour la détection des dits signaux, ce dit premier étage étant couplé à la fibre optique (11) et étant conçu pour réaliser la détection hétérodyne des limites de phase et des limites de quadrature de phase du signal de battement produit à partir du signal polarisé reçu par la fibre optique (11) et du signal de l'oscillateur optique local, caractérisé en ce que le dit premier étage comprend de plus quatre filtres passe-bande (20-23) centrés autour de la fréquence intermédiaire des signaux détectés par les dites photodiodes (16-19), et en ce qu'un second étage (24,32) est prévu qui est couplé au dit premier étage et conçu pour démoduler les signaux reçus afin de fournir le signal multiniveau, comportant un dispositif électronique qui convertit les signaux de fréquence intermédiaire des dits filtres passe-bande (29-32) en une bande de base et comprenant une boucle de verrouillage de phase (28), quatre multiplicateurs (24-27) et quatre filtres passe-bande (29-32), et en ce qu'un circuit de traitement est couplé au dit second étage et est conçu pour comparer le dit signal multiniveau à des signaux de référence prédéterminés.

7. Récepteur optique selon la revendication 6 pour la réception de signaux multiniveau formés selon le procédé de la revendication 2 ou 3, caractérisé en ce que le dit circuit de traitement, basé sur l'évaluation

de la matrice de Jones inverse, comprend quatre circuits (34-37) qui reçoivent à leurs entrées les signaux de bande de base provenant des filtres passe-bande (29-32), qui calculent les moyennes de temps des dits signaux dans des périodes de temps beaucoup plus longues que la période de symbole et beaucoup plus courtes que les périodes caractéristiques des fluctuations de polarisation, et qui fournissent à leurs sorties quatre signaux représentant les dites moyennes de temps, un circuit pour l'inversion de la matrice de Jones (33) recevant à son entrée les signaux de bande de base mentionnés ci-dessus et fournissant à sa sortie les valeurs estimées du signal multiniveau transmis, un circuit de calcul (38) dont l'entrée reçoit les quatre signaux représentant les moyennes de temps des signaux de la bande de base et qui compare les dits signaux aux symboles possibles transmis formant les signaux de référence prédéterminés emmagasinés dans le circuit lui-même de façon à calculer les coefficients de la matrice de Jones et à les fournir au circuit pour leur entrée dans la matrice de Jones (33), et un circuit de décision (39) dont l'entrée reçoit les valeurs estimées du signal multiniveau transmis et qui compare les dites valeurs aux symboles possibles transmis emmagasinés dans le circuit lui-même de façon à assigner à chaque valeur estimée l'un des symboles possibles transmis.

8. Récepteur optique selon la revendication 6 pour recevoir des signaux multiniveau formés selon le procédé de la revendication 2 ou 3, caractérisé en ce que le dit circuit de traitement comprend un premier dispositif à circuit (45) pour déterminer initialement les signaux de référence par une séquence d'initialisation, un second dispositif à circuit (40) conçu pour calculer la moyenne de temps des signaux de la bande de base dans des périodes de temps beaucoup plus longues que la période de symbole et beaucoup plus courtes que la période caractéristique des fluctuations de l'état de polarisation, et pour emmagasiner et mettre à jour les composantes de signaux de référence, le dispositif à circuit de décision (45) étant conçu pour comparer les moyennes de temps, des signaux de bande de base aux signaux de référence, et pour assigner à chacun d'eux l'un des symboles possibles transmis, la période de temps de mise à jour étant beaucoup plus courte que la période caractéristique des fluctuations de polarisation et beaucoup plus longue que la période de symbole.

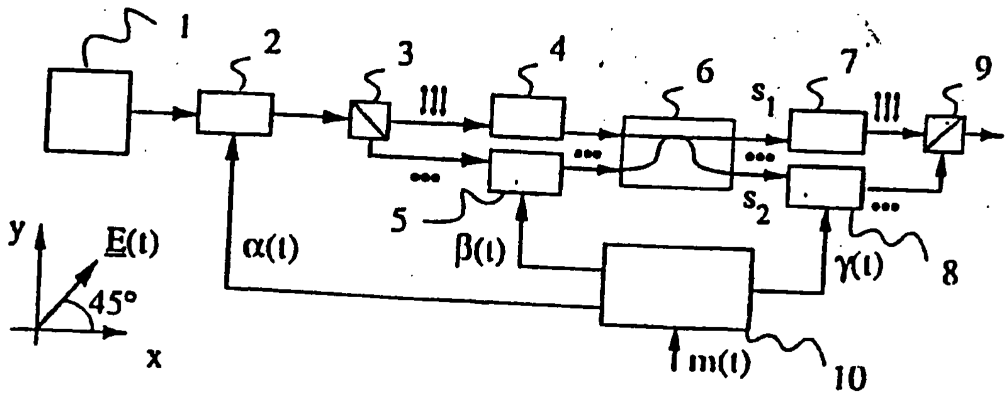
1
2
3
4
5
6
7
8
9
10
s1
s2
y
x
E(t)
45°
α(t)
β(t)
γ(t)
m(t)

Fig. 1

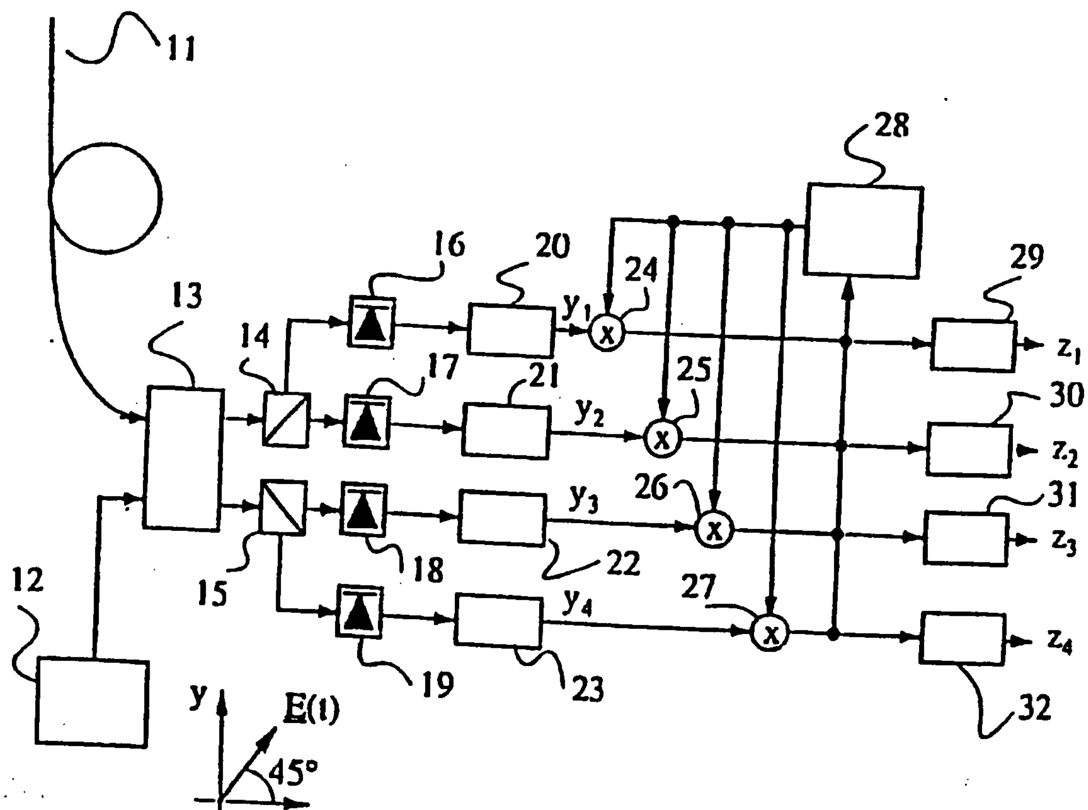
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
y1
y2
y3
y4
z1
z2
z3
z4
x
y
E(t)
45°

Fig. 2

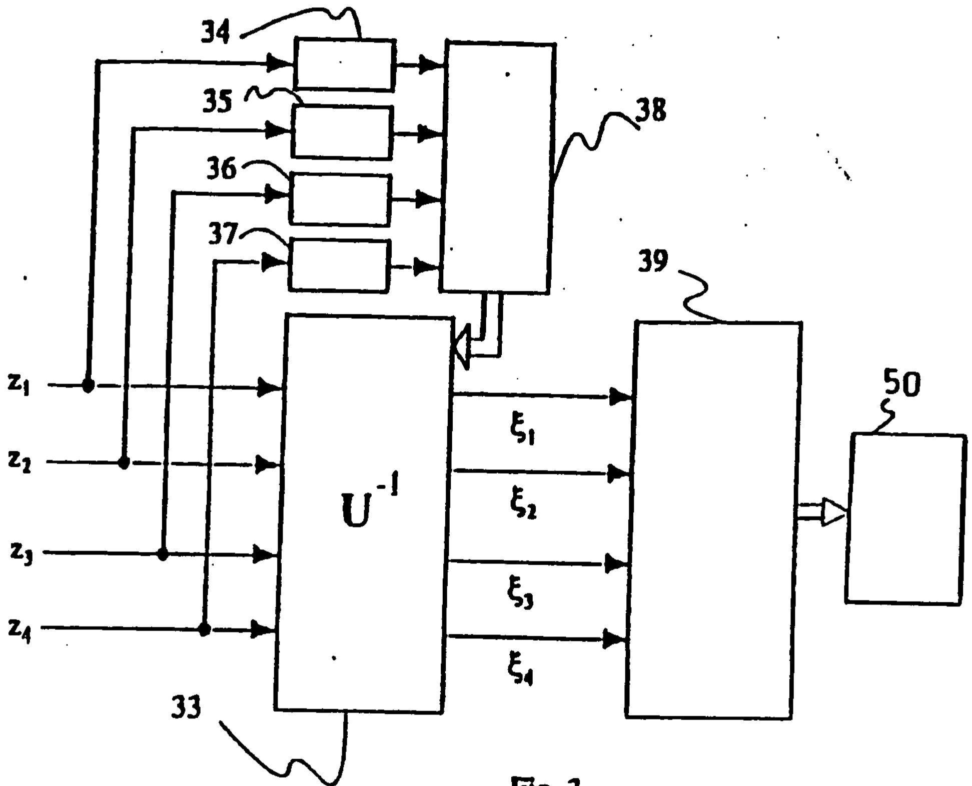
34
35
36
37
38
39
50
z_1
z_2
z_3
z_4
U^{-1}
ξ_1
ξ_2
ξ_3
ξ_4
33

Fig. 3

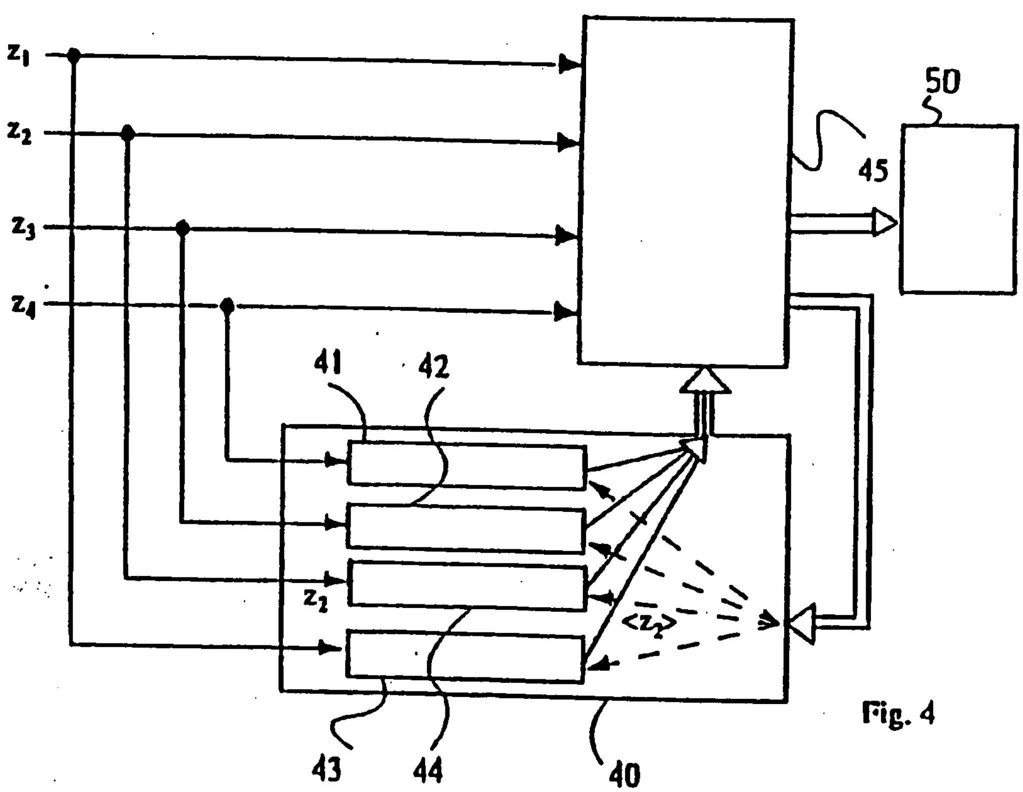
z_1
z_2
z_3
z_4
50
45
41
42
z_2
$\langle z_2 \rangle$
43
44
40

Fig. 4

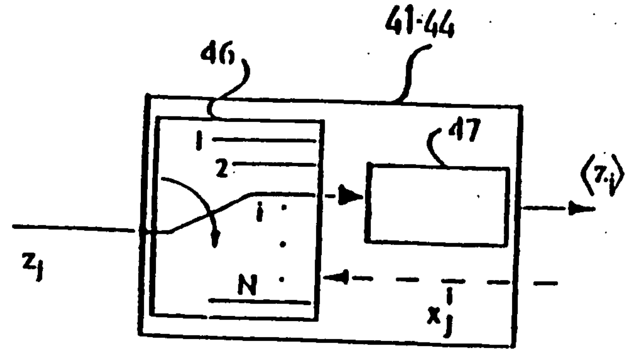
41-44
46
47
1
2
i
N
z_j
$\langle z_j \rangle$
x_j^i

Fig. 5

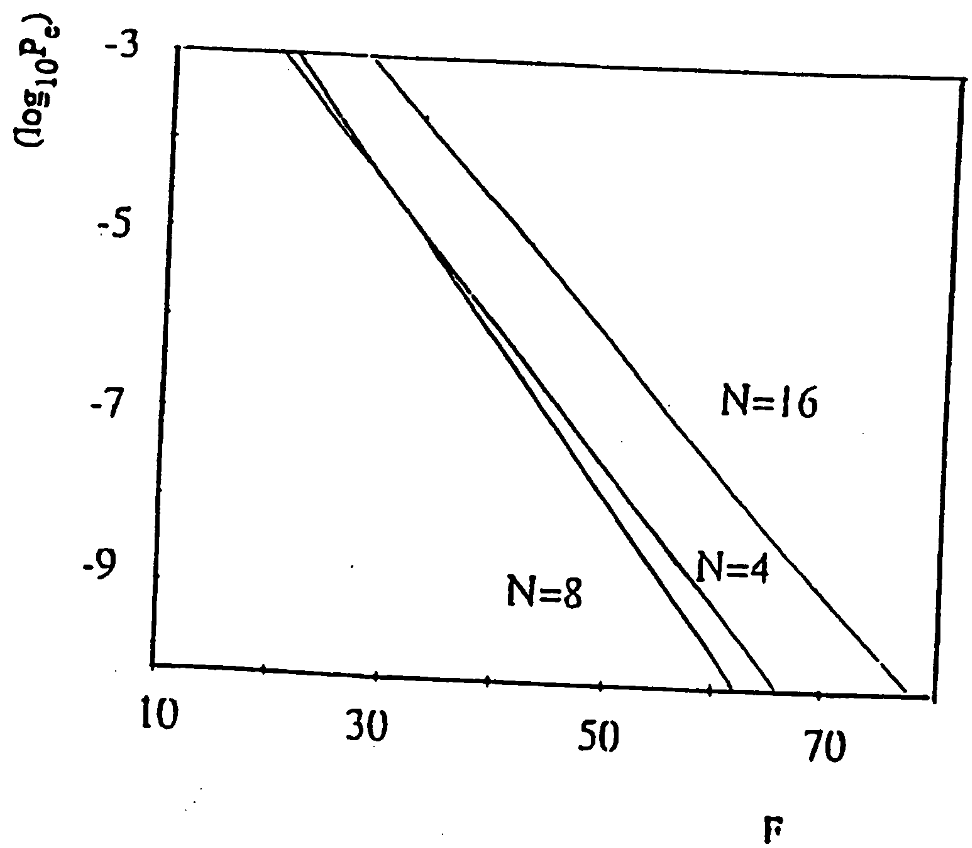
$(\log_{10}P_e)$
-3
-5
-7
-9
10
30
50
70
F
N=16
N=4
N=8

Fig. 6

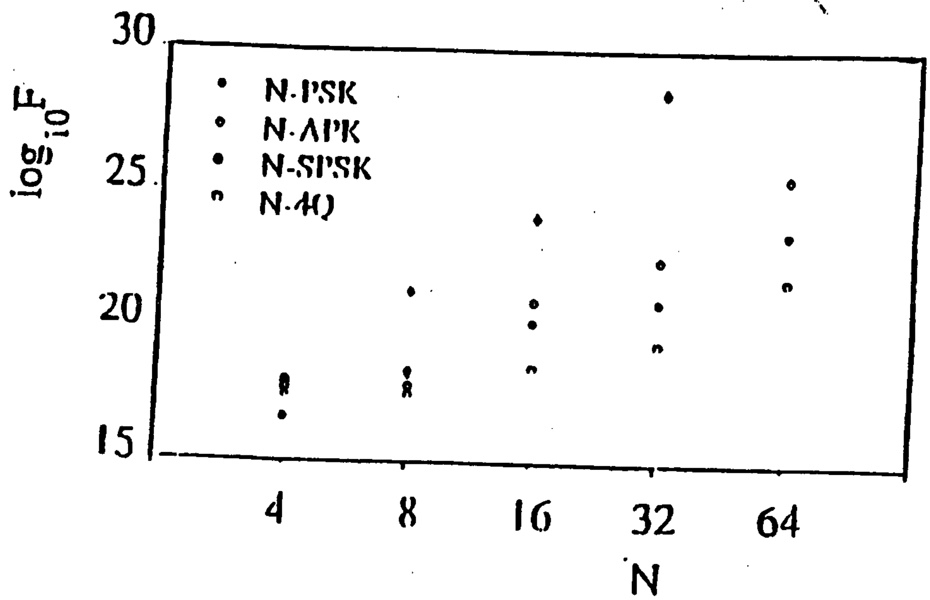
30
25
20
15
$\log_{10} F$
N-PSK
N-APK
N-SPSK
N-4Q
4
8
16
32
64
N

Fig. 7

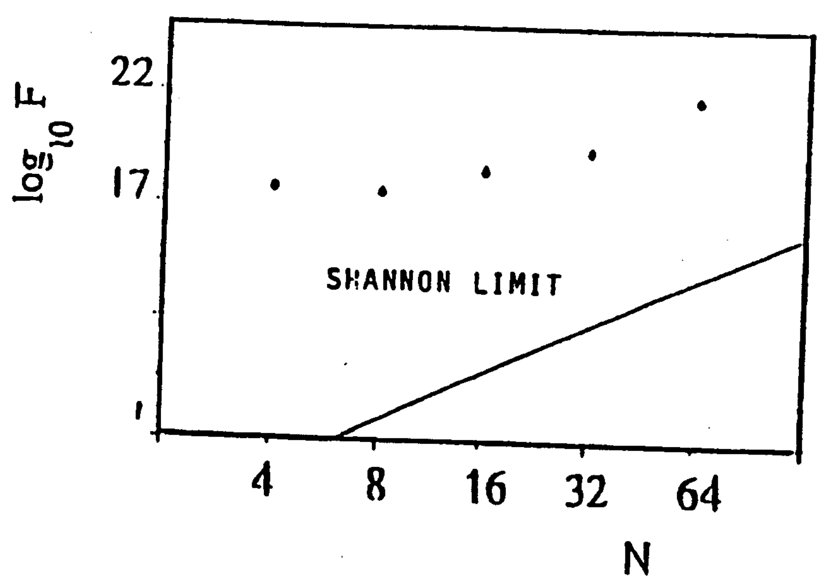
22
17
1
$\log_{10} F$
SHANNON LIMIT
4
8
16
32
64
N

Fig. 8